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Quest for toroidal freeze-out configuration in the central ^{197}Au + ^{197}Au collisions at 23 AMeV

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Abstract

We present the results of the experiment performed by the CHIMERA collaboration with the 4π CHIMERA array, for the system $^{197}Au + ^{197}Au$ at 23 AMeV. The experimental data are compared with ETNA and QMD model predictions. Efficiency factor is used as an indication of the formation of an exotic freeze-out configuration. Comparison between experimental data and model predictions may indicate the formation of flat/toroidal nuclear systems.

The search for exotic nuclear configurations was inspired by J.A.Wheeler [1]. Theoretical investigations related to the synthesis of long-living nuclei beyond the island of stability have shown that they can be reached only if non-compact shapes are taken into account. Calculations for bubble structures showed that such nuclei can be stable for $Z > 240$ and $N > 500$ (see e.g. [2]). Recently it was found that for nuclei with $Z > 140$ the global energy minimum corresponds to toroidal shapes [3]. In contrast to bubble nuclei, the synthesis of toroidal nuclei is experimentally available in collisions between stable isotopes.

To address this issue simulations were done for Au + Au collisions in a wide range of incident energies using the BUU code [4]. These calculations indicate that the threshold energy for the formation of toroidal nuclear shapes is located around 23 MeV/nucleon.

A dedicated experiment for the Au + Au reaction at 23 AMeV was performed using the CHIMERA detector at INFN-LNS [5]. The data analysis is presented in [6, 7]. In our present analysis we use a class of complete events for which the total charge of identified fragments is close to total charge of the system and total parallel linear momentum is close to linear momentum of the projectile.

For the class of events with five fragments one can consider at least two mechanisms responsible for the presence of the fifth heavy fragment: (i) creation of the fragment in the interaction region (intermediate velocity source) for more peripheral collisions or (ii) the multifragmentation of the composite nuclear system formed in central collisions.

In order to investigate the reaction scenario responsible for events with five and more fragments we have compared experimental data with ETNA and QMD model predictions [8]. In ETNA model three freeze out configurations are considered:(i) ball geometry with volume 3 and 8 times greater than normal nuclear volume V_0; (ii) fragments distributed on the surface of the sphere mentioned above (bubble configuration); (iii) fragments distributed on the ring with diameter 12 fm and 15 fm (toroidal configuration). In this model we consider only events corresponding to central collisions (0-3 fm impact parameter range). In order to simulate the contribution from noncentral collisions the QMD model calculations were performed [9] in the full impact parameter range 0 - 12 fm.

In our analysis several observables sensitive to the freeze-out configuration are investigated. The δ, and Δ^2 observables as most sensitive to the shape of freeze out configurations were selected [8]. In the Fig. 1 (left picture, left panels) the δ distributions are presented for experimental data, ETNA model predictions for considered freeze-out geometries and QMD predictions. One can see here that the δ distribution for experimental data is similar to that corresponding QMD predictions. The Δ^2 distributions are shown in Fig. 1 (left picture, right panels) for data and model predictions. One can see here that for Δ^2 variable the biggest difference between experimental distribution and model predictions is observed for the Ball $8V_0$, and Bubble $8V_0$ configurations.

In relation with Δ^2 and δ parameters the θ_{plane} and θ_{flow} angles were defined. In our analysis a correlation between θ_{plane} and θ_{flow} angles was investigated. For experimental data most of events are located in the region selected by conditions $\theta_{flow} < 20^o$ and $\theta_{plane} > 75^o$. The same behavior is observed in the case of QMD calculations. For the Ball $8V_0$ configuration one observes the correlation between θ_{flow} and θ_{plane} angles. For toroidal configuration the correlation between these angles is even stronger. Most of these events are locate in the region defined by conditions $\theta_{flow} > 20^o$ and $\theta_{plane} < 75^o$.

Following the method proposed in Ref. [8] we select events corresponding to toroidal shape by the set of conditions: $\Delta^2 < 0.001\ c^2,\ and\ \delta < 0.05$. As an efficiency measure of the above conditions we take the ratio of events number fulfilling the selection conditions to the number of events with five and more heavy fragments (EF, efficiency factor). The results of this procedure are presented in the Fig. 1 (right picture). for different regions of θ_{flow} and θ_{plane} angles. As one can see the EF is very low for spherical freeze-out configurations with respect to the corresponding values for toroidal configurations.

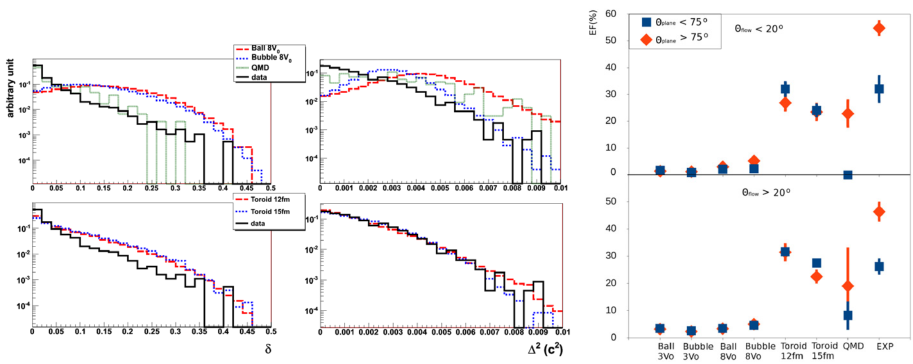

Figure 1: At left picture the δ distributions (upper left panel) are presented for experimental data, Ball $8V_0$, Bubble $8V_0$ freeze-out geometries and QMD predictions. In the bottom left panel the experimental distribution is compared with predictions for Toroid 12 fm and Toroid 15 fm configurations. In the right panels the Δ^2 distributions for experimental data and model predictions are shown. All the distributions presented here are constructed using the condition $Z_{frag} \geq 10$ and $\theta_{flow} > 20^o$. At right picture the EF values for different windows of θ_{plane} and θ_{flow}. The presented results were calculated using the condition $Z_{frag} \geq 10$.

The efficiency factor is strongly dependent on the θ_{plane} range for QMD calculations. For experimental data the value of the efficiency factor is about 50% for events located in the reaction plane ($\theta_{plane} > 75^o$) and is reduced by factor of 2 for events perpendicular to the reaction plane. These values are weakly dependent on the θ_{flow} angle range. One observes that the values of the EF for experimental data are much larger than the corresponding predictions for QMD model. The biggest difference is observed for events located outside the reaction plane ($\theta_{plane} < 75^o$) at small θ_{flow} angles. In this case the QMD model prediction is close to zero.

In order to investigate possible formation of toroidal configurations in our analysis we selected the region where according to ETNA predictions the toroidal configurations are expected in the θ_{flow} and θ_{plane} plane ($\theta_{plane} < 75^o$ and $\theta_{flow} > 20^o$). Here one can notice that the EF values for experimental data are very close to the model predictions for toroidal configurations. This observation may indicate the formation of toroidal/flat freeze-out configuration created in the Au + Au collisions at 23 MeV/nucleon.

Results obtained for other observables suggest that the formation of toroidal configurations can be related to a small fraction of flat events tilted with respect of the reaction plane ($\theta_{plane} < 75^o$). The nature these events should be explained. The probability for these events is much greater than the prediction of the QMD model.

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